



LABORATORY INVESTIGATION OF VARIABLE SPEED CONTROL OF SYNCHRONOUS GENERATOR WITH A BOOST CONVERTER FOR WIND TURBINE APPLICATIONS

Sharma, Ranjan; Rasmussen, Tonny Wederberg

Published in:
EWEC2008

Publication date:
2008

Document Version
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):
Sharma, R., & Rasmussen, T. W. (2008). LABORATORY INVESTIGATION OF VARIABLE SPEED CONTROL OF SYNCHRONOUS GENERATOR WITH A BOOST CONVERTER FOR WIND TURBINE APPLICATIONS. In *EWEC2008* (1 ed., Vol. Scientific Proceedings). European Wind Energy Association (EWEA).

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Laboratory Investigation of Variable Speed Control of Synchronous Generator With a Boost Converter for Wind Turbine Applications

Ranjan Sharma
Technical University of Denmark
ransharma@gmail.com

Tonny W. Rasmussen
Technical University of Denmark
twr@oersted.dtu.dk

Abstract

This paper includes the experimental and simulated results of variable speed control of a synchronous generator. To achieve controlled variable speed operation, the synchronous generator is loaded with a three phase rectifier and a boost converter. The terminal voltage of the generator can be controlled from the converter's duty cycle if output voltage of the converter is kept constant. This constant voltage is achieved with the help of a grid side inverter. As the speed and the terminal voltage of the generator are directly related to each other, its speed can be controlled for a given torque. An experimental setup of a 7.5KVA generator is prepared to verify system response. Some interesting aspects concerning distributed capacitance of the generator winding and non-linear speed vs duty-cycle response are observed. Cause and effect of such problems are discussed in this paper. Efficiency measurement showed some promising results and the overall system response is found positive. Also a Matlab simulation is performed for single turbine system including grid side inverter. The results are presented here in brief.

Keywords: Wind turbines, variable speed, synchronous generator, boost converter

control can be reduced and theoretically the annual energy production will be improved.

Variable speed turbines equipped with double-fed induction machine or simply induction machine are common. The focus in this paper will be on using synchronous generator controlled with boost converter, initially proposed in [1]. The synchronous generator can either be a permanent magnet or wound rotor type. A wound rotor type generator will have an extra degree of freedom in terms of field excitation, but at the same time, loss in the rotor circuit will be present. In the other hand, permanent magnet generators are relatively expensive. However, the proposed system to control the speed of a synchronous generator will require less number of switching devices compared to the control of induction or double fed induction generators. Hence, this will reduce switching and conducting losses. Many wind turbines in a farm can be connected to a common dc link point as shown in figure (1). The power transmission will be through HVDC (high voltage direct current) lines and the IGBT equipped main inverter will connect the farm to the grid. The proposed configuration of a wind farm will also allow individual control of each turbine with maximum power point tracking [2]. With the help of the boost converter duty cycle, power from the generator can be regulated. Depending upon the power available in the wind, the duty cycle can be varied to control the speed. During the process, the electrical power to the grid will be constant and thus the power quality is improved.

1 Introduction

Variable speed wind turbines have been of major interest recently due to its superiority over fixed speed on different aspects. Some advantages are that, a variable speed wind turbine together with pitch control can be used for smooth power regulation, mechanical stresses on the turbine components can be reduced, complexity of the pitch

2 Speed Control of Synchronous Generator

If a single generator system is considered, the equivalent diagram of the system can be represented as shown in figure 2. The dc side can be

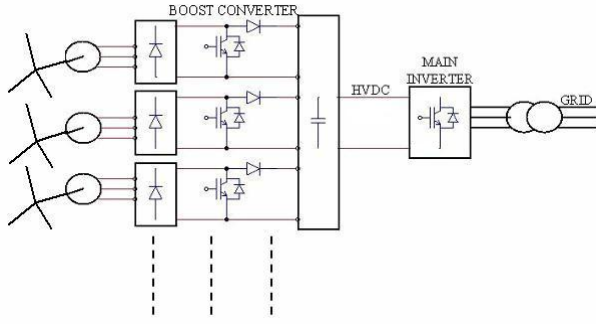


Figure 1: Proposed wind farm connection diagram

represented by variable dc voltage whose magnitude can be controlled by a boost converter. Since the output voltage of the boost converter is constant, any change in its duty cycle will force change the input dc voltage. The terminal voltage of the generator is determined by this variable dc voltage. Since the voltage across and current through a diode are in phase, the load and the rectifier can be assumed to draw unity power factor current. For the magnitude of power transferred from the generator to the load, the losses in the rectifier can be neglected for the analytical purpose.

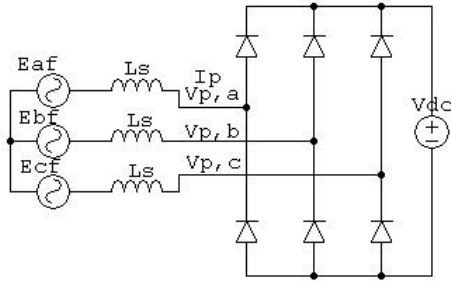


Figure 2: Synchronous generator with rectifier and voltage load

For a synchronous generator, either permanent magnet or wound rotor supplied with a fixed field current, the generator excitation voltage can be written as,

$$E_{af} = K_\phi \omega_e \quad (1)$$

Where $\omega_e = 2\pi f$ is the electrical angular frequency and $K_\phi = 4.44\phi_{af}NK_w$ is a generator constant provided that ϕ_{af} is constant.

So for a variable speed operation, generator voltage equation can thus be written as,

$$\frac{V_p}{\omega_e} \angle 0^\circ + jL_s I_p = K_\phi \angle \delta^\circ \quad (2)$$

Where δ is the power angle, V_p is the phase voltage, I_p is the current and L_s is the inductance of the generator. The phasor diagram representation of the generator is shown in figure 3.

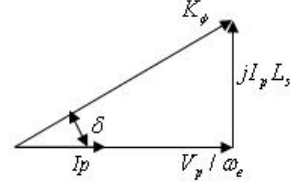


Figure 3: Phasor diagram

The DC values after the rectifier can be written in terms of generator AC voltage and current.

$$V_{dc} = \frac{3\sqrt{6}}{\pi} V_p \quad (3)$$

$$I_{dc} = \frac{\pi}{\sqrt{6}} I_p \quad (4)$$

From the phasor diagram, phase current of the generator can be written as,

$$I_p = \frac{K_\phi}{L_s} \sqrt{\left[1 - \left(\frac{\pi V_{dc}}{3\sqrt{6} K_\phi \omega_e}\right)^2\right]}$$

Therefore the power and torque equations will be as follows,

$$P = 3V_p I_p = 3 \frac{\pi V_{dc} K_\phi}{3\sqrt{6} L_s} \sqrt{\left[1 - \left(\frac{\pi V_{dc}}{3\sqrt{6} K_\phi \omega_e}\right)^2\right]} \quad (5)$$

$$\tau = \frac{3V_p I_p}{\omega_m} = 3p \frac{\pi V_{dc} K_\phi}{3\sqrt{6} 2\omega_e L_s} \sqrt{\left[1 - \left(\frac{\pi V_{dc}}{3\sqrt{6} K_\phi \omega_e}\right)^2\right]} \quad (6)$$

Since the load current has unity power factor, no reactive power transfer takes place. Equations 5 and 6 show the relation between V_{dc} , τ , and ω_e . Solution for different dc voltage levels are plotted in figure 4. It can be observed that by changing

V_{dc} or the generator terminal voltage, speed can be controlled to regulate the power. Else the dc voltage can also be controlled to track the desired torque for different wind speed. Here the focus will be on power regulation.

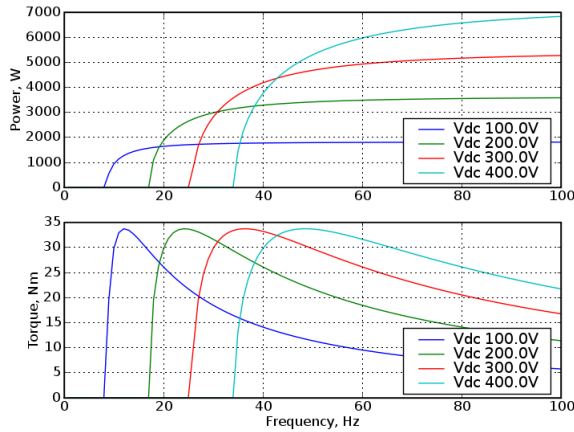


Figure 4: Power and Torque variation with frequency

3 Experimental Setup

An experimental setup is build to test the behavior of the system under the above explained conditions. A lab setup is made for a small $7.5kVA$ salient pole wound rotor synchronous generator. It is believed that the basic characteristics of the generator will be similar to the big ones used in high power rated turbines. However, parameters like power to loss ratio can be expected to differ in large machines compared to the small ones and some specific modifications might be necessary.

Figure 5 (next page) shows the experimental setup layout. An electronic load controlled by an IGBT is used to keep the voltage at the booster output constant. The whole system is kept floating with the help of isolated power supplies closely representing a situation of a real wind turbine. The inductance of the generator itself is used as a boost inductor. In this case, boost inductance is the sum of two inductances of two different phases. Results verify that the generator inductance is big enough for the purpose. This will not only reduce an extra component (usually expensive for high power) in the system but also reduces the parasitic loss associated with an inductor.

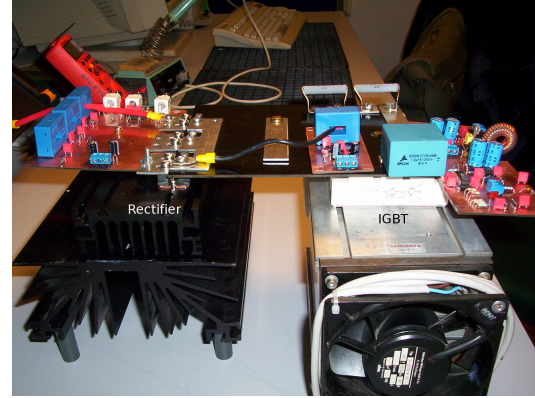


Figure 6: Boost converter picture

4 Experimental Results

To verify the boost converter performance, the generator is run at $1500RPM$. The dc link voltage is kept constant at $300V$ and the boost converter is switched with a $2KHz$ gate signal. Measurement of voltage across line to line of the generator and the dc current is shown in figure 7. During each switching, a spike in the current measurement can be observed. These spikes increases with increase in generator terminal voltage. So as a check, the generator is then replaced by a three phase variable transformer and the same experiment is repeated. These spikes in current does not appear with such high magnitudes which proves that they are not due to the junction capacitance of the diodes or any other paracitic capacitors in the circuit. The conclusion thus is that they appear from the winding paracitic capacitance of the generator. Since the winding capacitance is less in the transformer, only smaller spikes of current are seen. The per phase winding capacitor is a lumped effect of different distributed capacitors like between winding to winding, turn to turn, turn to core, turn to terminals etc. For a similar condition of winding capacitors, a simulation model is prepared in P-Spice; very similar spikes are observed.

Measured per phase capacitance of the generator is $75nF$. At higher generator voltage level, these spikes are too large compared to the rated generator current and could cause damage to the generator winding upon continuous operation. An inductor or a passive filter can be used to supress these spikes. However some major problems do appear;

- *Extra added component/s* - these components for high power applications are huge and costly.

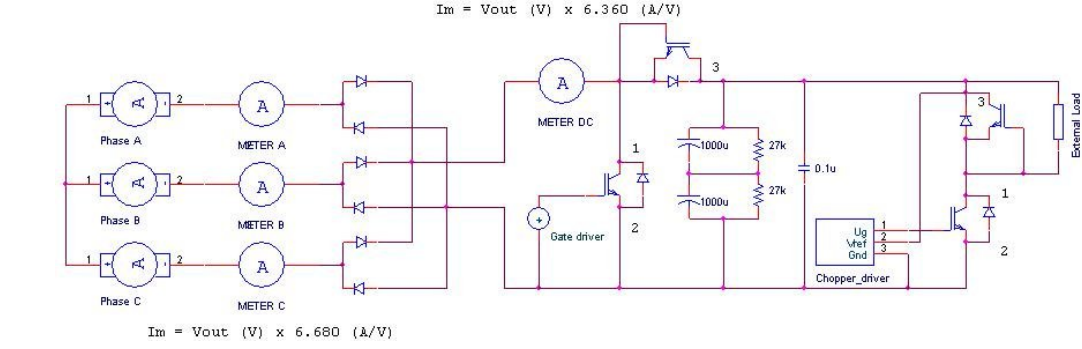


Figure 5: Experimental setup layout

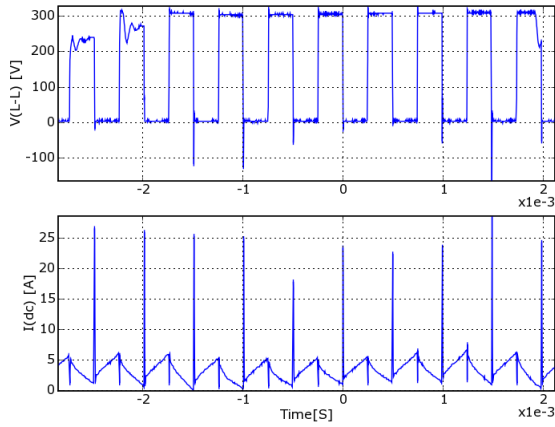


Figure 7: Continuous mode of operation of the converter

- *Winding capacitance in the added inductor itself.*
- *Two sets of resonating frequencies - during on and off conditions of the converter switch, the equivalent impedance of the system will vary. This will produce two different sets of resonating frequencies in the current spike during damping. It is difficult to select right value of inductor for both the cases.*
- *Higher resistance is required in series to damp the oscillation fast - this results higher loss.*

4.1 Reduced di/dt technique

The rise time of the current spikes are relatively fast ($10A/\mu S$) compared to the rise time of normal switch current as seen in figure 7. Thus the switching time of the IGBT can be slowed down in such a way that it does not allow the spike current to pass. But it should not be too slow to affect the rise

of normal switch current. This will, however, introduce extra switching loss, thus a compromise is required. The consequences of slow switching on the turn on loss can be seen in figure 8. Smaller di/dt of the collector current, I_c , would mean higher turn on loss. The di/dt of an IGBT can be altered by changing the time constant of the gate voltage rise. Time constant is defined as [4],

$$\tau = R_g(C_{gs} + C_{gd}) \quad (7)$$

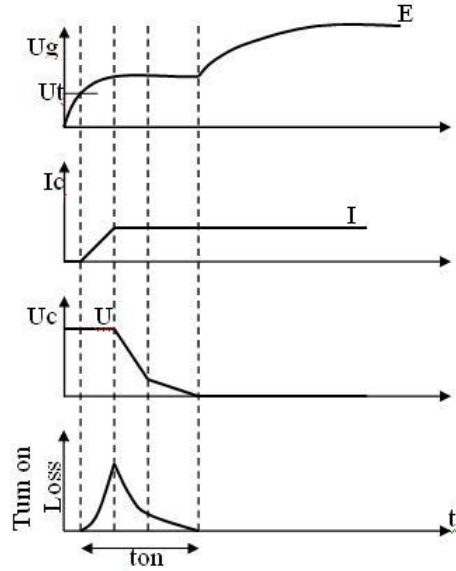


Figure 8: Switching sequence of IGBT

Where C_{gs} and C_{gd} are the characteristic capacitance value of an IGBT and R_g is the gate resistance which can be manually adjusted to alter the switching. However, it is not required to slow the switching sequence (and increase the switching loss) during turn off process. The current during turn off is used by the generator capacitor to

charge itself. So the switching circuit of the IGBT is made as shown in figure 9.

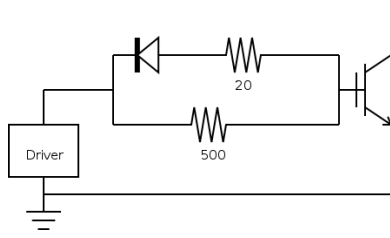


Figure 9: Modified gate driver

A new value of the gate resistance for turn on is calculated such that the spike current is below the rated generator current for full load operation while the turn on loss is also tolerable. The new di/dt value is determined theoretically, experimentally and from simulation and are presented below.

Theoretical - $45A/\mu S$

Measured - $41A/\mu S$

P-spice simulated - $39A/\mu S$

Efficiency of the rectifier converter system is measured with the new configuration of reduced di/dt for both continuous and discontinuous mode of operation. The result for 50% duty cycle is shown in figure 10. At half the full load of the generator, the measured efficiency is 95.5%.

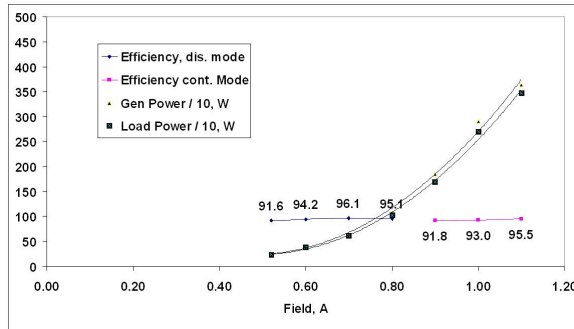


Figure 10: Efficiency measurement

Simultaneously, efficiency is measured in a simulation model (P-spice) as well. Simulated and measured efficiency values are close. Due to the driver motor rating, the full load efficiency measurement was not possible in the laboratory. So for full load, efficiency calculation is done in P-spice and the value obtained is 97.1%. It is imperative to note that the IGBT and rectifier diodes used in the experiments are higher rated than required. So, optimized semiconductor selection and use of right snubber components will further increase the full

load efficiency. The current spikes after increasing the gate resistance during turn on sequence is shown in figure 11. It shows that the spikes have been reduced significantly in comparison to normal IGBT operation, while the efficiency is also within safe limits and can further be improved.

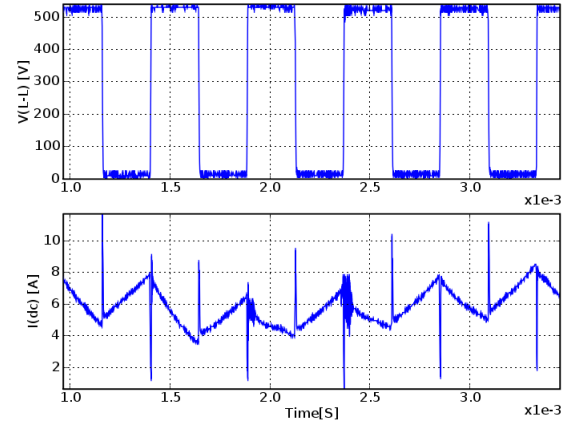


Figure 11: DC current after reduced di/dt

4.2 Speed Control

From theory, a linear response of speed/duty-cycle is expected. The measurements, however, showed a nonlinear response. Figure 12 is taken at constant torque while the duty-cycle of the converter is varied.

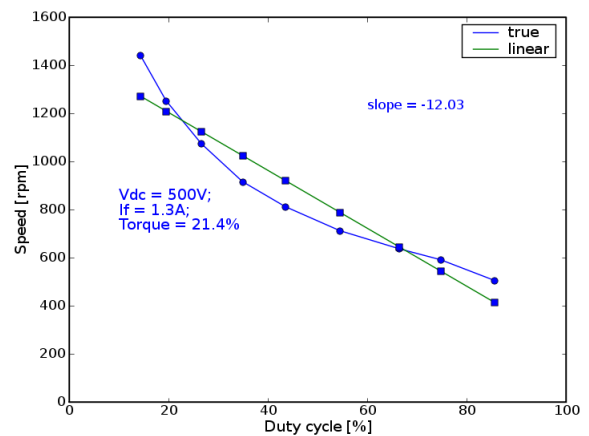


Figure 12: Speed vs duty-cycle

Since the torque is constant, for the speed to be non-linear, it is the power that has to be non-linear. So power measurements were done at different

points in the system. The load power is approximately linear, but the losses in the generator were not, and as a result of that the speed is also not linear. The major losses in the generator are copper loss, core loss (hysteresis and eddy current) and friction and windage loss. Copper loss is approximately linear so could be neglected. Figure 13 shows the measurement of different losses. Not included in the figure are, the converter and rectifier losses. These losses are normally not linear due to dynamic resistance of the semiconductor, but are very small compared to the generator loss. So it could be neglected as well.

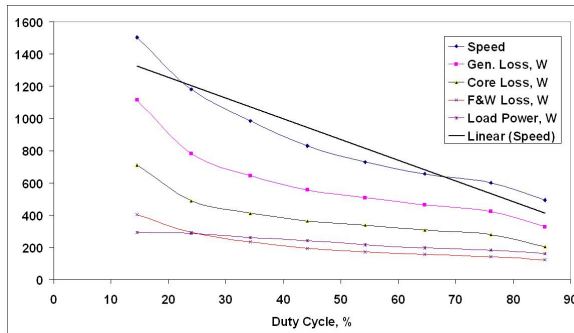


Figure 13: Generator loss measurements

This non-linearity is very important in case of control system design and needs consideration. Though these losses can't be eliminated, the non-linear effect can be compensated with an intelligent control system.

5 Simulation Results

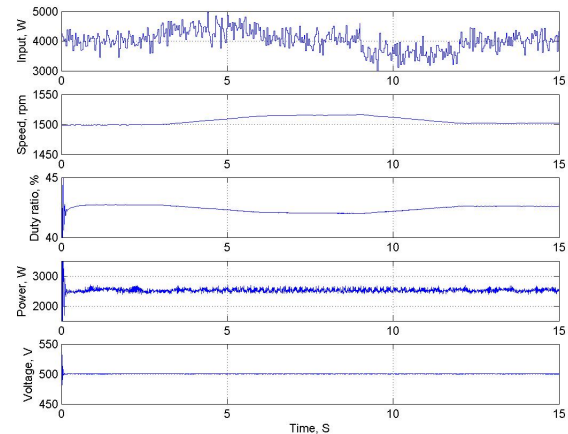
A simulation model of a single turbine system is prepared in Matlab®, simulink. The model includes: generator, rectifier, dc-dc converter, grid side inverter and control system as shown in figure 14 (next page). Mechanical model of the turbine is not included considering the already large simulation time. However, the input power to the system is set very close to the real condition representing stochastic wind. The boost converter control unit consists a PI controller. Since the dc link voltage is constant, output current after a low pass filter can be taken as a feedback to regulate the power. Depending upon the change in booster output current, duty cycle will vary to change the speed of the generator and maintain a regulated output power.

The grid side inverter model is an analog model which avoids the switching sequence of the switches, again saving enormous simulation time.

The inverter is modeled as a three phase voltage controlled voltage source. The main disadvantage of the analog model is that the harmonics content associated with normal inverters can not be simulated. The purpose is to study the interaction of the generator with the boost converter control system and the inverter control system and check the system response in varying input power.

The inverter controller control strategy consists of three main loops. The active loop controls the dc link voltage, the reactive loop controls the reactive power flow between the grid and the inverter and the inner current loop controls the current in the system. Throughout all these simulations, the reference dc side voltage is set at 500V dc value.

The aim is to be able to deliver a constant power throughout the fluctuation in wind or input power, while storing or releasing the energy from the rotating mass inertia. However, this phenomenon is only possible if the change in input and duration of change are not very large. If otherwise, the speed will have to change a lot and the system might end up in an unstable situation. In such case, the pitch control mechanism of the blades will need to take over. This simulation does not include the mechanical part, so only relatively small variation in input power is simulated. The result can be seen in figure 15.



Input : Input mechanical power to the machine
Power : Power delivered by the inverter to the grid
Voltage : DC link voltage

Figure 15: System response for varying input power

It can be observed that the speed responds to the input power as dictated by the duty ratio. The quality of the power delivered in terms of fluctuation is improved compared to what would have been for

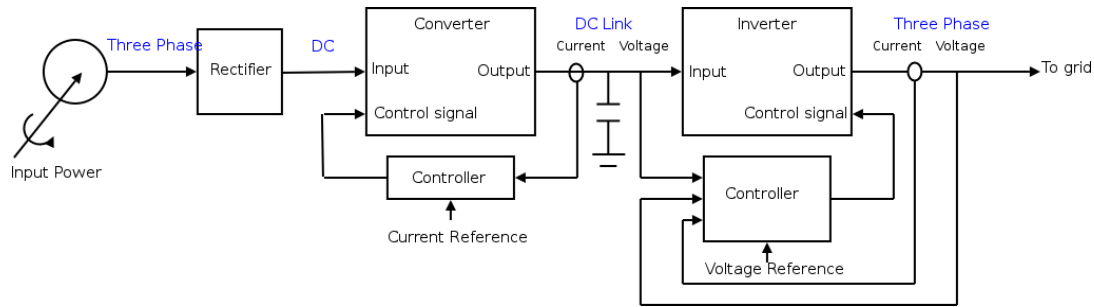


Figure 14: One line diagram of Matlab model

a constant speed wind turbine. A constant current reference is used in the booster control unit. Thus, the power output from the inverter to the grid is constant. This current reference can also be generated with reference to wind speed such that the slow variation in wind speed is followed but not the gusts. Also this current reference can be adjusted to allow power regulation together with pitch control, simulated results and verifications can be found in [2].

6 Conclusion

The speed or the frequency control of the generator is thus possible by controlling the terminal voltage. This configuration also allows individual control and power regulation of the turbines.

Unlike with induction generator it is possible to use diode, line commuted rectifiers, with synchronous generator because the power flow need not be in both directions. This is advantageous in terms of cost and complexity of the system. The worst case efficiency measurement of the rectifier and converter is satisfactory and well within tolerable limits. But the generator and semiconductor components used can be optimized to further improve the system efficiency. Some of the major issues such as non linear speed variation with duty ratio, that need to be considered during the system design have also been established.

Acknowledgment

This work is a part of a masters thesis [3] prepared at Technical University of Denmark, DTU, by Ranjan Sharma under the supervision of Ph.D. Tonny Rasmussen. The authors like to thank all the faculties and staffs at Ørsted - DTU.

References

- [1] J. Kass Pedersen, "Power transmission from large offshore wind farms", UEPC'99, Universities Power Engineering Conference, Leicester 1999.
- [2] M.O. Comino, "Power transmission from variable speed wind turbine equipped with synchronous generator", MSc. thesis, Technical University of Denmark, 2006.
- [3] Ranjan Sharma, "Laboratory investigation of variable speed control of synchronous generator with a boost converter", MSc. thesis, Technical University of Denmark, 2007.
- [4] A. Hansen, H. Havemann, J. K. Pedersen, T.W. Rasmussen, "High power electronics", Oersted-DTU, Technical University of Denmark, 2006.